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A method to assess the in vitro optical quality of presbyopic solutions based on the axial modulation transfer function

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Abstract

Purpose: To present a metric for assessing the in vitro optical quality of rotationally symmetric optical elements based on volume calculation under the surface defined by the axial modulation transfer function (aMTF).

Setting: University of Valencia, Valencia, Spain.

Design: Experimental study.

Methods: The metric (Volume Under the axial MTF or VUaMTF) assessed the optical quality of two rotationally symmetric multifocal intraocular lenses (MIOLs) within various defocus intervals (0.5 D, 0.75 D and 1 D) and spatial frequency intervals (7.5 c/degree, 15 c/degree and 30 c/degree) as well.

Results: The far focus of the bifocal yielded higher volume values for all the spatial frequencies and defocus intervals comparing to the far focus of the trifocal. The results for the near focus were similar for both lenses. In addition, the trifocal yielded notable results for the intermediate distance.

Conclusions: VUaMTF proved to be a useful tool for an objective evaluation of the MIOLs. Moreover, it can be applied to evaluate the optical quality of every rotationally symmetric IOL or optical element.

Introduction

For assessing the imaging performance of an optical system it is necessary to set image quality criteria. These criteria are commonly defined by metrics derived by the Wavefront Error (WFE), the Point Spread Function (PSF) and the Optical Transfer Function (OTF).[1-4] Nevertheless, one single metric is not adequate to characterize entirely the quality of an optical system.[5] In previous studies focusing on human eye,[1-4] a plethora of 31 metrics have been classified into two types: pupil plane metrics (based on WFE) and image plane metrics (based on PSF and OTF). The correlation between these metrics in terms of optical quality and visual performance has been examined. Albeit some metrics proved to be better predictors than others, still there is not an ideal combination among them.[1,2]

In order to characterize the optical quality of an IOL, Modulation Transfer Function (MTF), the modulus of the Fourier Transform of the PSF, is the established scientific method widely used.[6,7] By definition, MTF expresses the variation of image contrast with spatial frequency for an object with 100% contrast,[2,7] or, in other words, how minutely a lens forms the image of an object. The MTF of an aberration-free optical system limited only by diffraction is called the diffraction limited MTF. The radial average MTF (rMTF) is the one-dimensional curve obtained by the averaged two-dimensional MTF across all directions. The majority of measuring devices dedicated to MTF estimation calculate the rMTF obtained by sagittal and tangential directions.[8]

Based on MTF, several metrics[2,7,9-11] have been developed. These metrics include the average modulation (the mean value of modulation at a range of frequencies), the area under the MTF, the Strehl Ratio by means of MTF (the ratio of the area under the actual MTF curve with the area under diffraction limited MTF curve) and the cut-off spatial frequency (the spatial frequency at which the modulation reaches or approaches to zero), among others.

An important factor that characterizes the optical performance of an IOL and of any optical system is the tolerance to defocus. This is particularly important for the MIOLs that have different foci. The measurement of MTF at a particular spatial frequency as a function of defocus is known as the Through Focus MTF (TF-MTF).[9] A variety of studies[10-19] has presented the TF-MTF in order to determine the optical quality of IOLs.

Another method to describe the performance of an optical system is the axial MTF (aMTF). The aMTF of an optical system is formed by successive MTF curves at different focal points across a range of spatial frequencies.[15] Therefore, the successive MTF curves create a surface that contains the information from the MTF and the TF-MTF. Thus, the aMTF describes the image-forming capability of an optical system as a function of defocus and spatial frequency.

In this paper we propose a metric, the Volume Under the aMTF (VUaMTF), for assessing the in vitro optical quality of rotationally symmetric optical elements. VUaMTF focuses on calculating the volume under the surface defined by aMTF at a certain maximum spatial frequency and within defined defocus intervals. Therefore, it aims to provide information about the optical tolerance to defocus and the optical quality at different spatial frequencies.

Methodology

VUaMTF scheme

Figure 1 is an example of aMTF of a bifocal IOL. The spatial frequency is given in cycles-per-degree (c/degree). Figure 1(a) represents the aMTF in a selected range of spatial frequencies (0 c/degree to 36 c/degree). The color bar that accompanies the figure indicates the MTF values. Far (0 D) and near foci (4 D) are clearly distinct in the graph: the far focus yields higher MTF values whereas the near focus yields lower MTF values. As the spatial frequency increases, the MTF values drop for both foci.

Figures 1(b) and 1(c) show in which way Figure 1(a) can be interpreted in order to obtain optical quality information by means of spatial frequency and defocus. Figure 1(b) shows that a horizontal profile (line 1) corresponds to the MTF of the far focus in the spectrum of spatial frequencies. On the other hand, Figure 2(c) shows that a vertical profile (line 2) can give information about the MTF in every IOL's plane at a particular spatial frequency. In this case, the 15 c/degree spatial frequency was selected which nearly corresponds to an optotype for 20/40 equivalent visual acuity in white light.[18]

The aforementioned profile corresponds to the TF-MTF, which is related to the defocus tolerance.

The calculation of the volume can be performed by setting intervals that isolate areas of interest. For example, the foci of a MIOL aim to provide good vision at different vergences and thus it is important to evaluate their optical quality. By setting intervals at the dioptric range of the lens, it is feasible to isolate and calculate the volume under the main foci. Figure 1(a) shows how the far foci of the bifocal lens can be isolated when a defocus interval (1 D) is set at a selected range of spatial frequencies (0 c/degree to 15 c/degree). Then, VUaMTF can be applied to calculate the volume within the defocus interval (Dy) for that range of spatial frequencies (Dx).

The selection of the intervals relies on the characteristics of the optical system (MIOLs in this case) that someone wants to examine. The different intervals can be set in both axes of the aMTF. Different ranges at the spatial frequency axis can be related directly to different visual acuities (e.g. 36 c/degree corresponds to an approximate VA of 20/20). Moreover, several intervals can be selected in the defocus axis and compare the optical performance at different vergences.

MIOLs Designs

In order to test the capability of VUaMTF, aMTF data from two MIOLs were used. Both MIOLs were aspherical with a diffractive design. One lens was bifocal and the other trifocal. Both lenses have optical diameter of 6.0 mm, overall diameter of 11.0 mm, incorporate ultraviolet blockers and are available in the market from 0 D to +32 D (in steps of 0.5 D).

The bifocal lens was the AT LISA 809M IOL (Carl Zeiss Meditec AG, Jena, Germany), with a +3.75 D near addition and nominal power of +20 D. The lens' optics distributes the light energy asymmetrically, directing 65% to the far focus and 35% to the near focus. The trifocal lens was the AT LISA tri 839MP IOL (Carl Zeiss Meditec AG, Jena, Germany), with a +3.33 D near addition and +1.66 D intermediate addition within the central 4.34 mm optical zone of the lens. The nominal power was +19 D. For pupils up to 4.34 mm the light energy distribution is 50% for the far focus, 20% for intermediate focus, and 30% for the near focus. Beyond the 4.34 mm central zone, the lens is solely devoted to far and near vision.

Optical Quality Assessment

The optical quality of the MIOLs was assessed with the PMTF instrument (Lambda-X, Nivelles, Belgium) using an aberration-free artificial cornea. The device complies with the ISO standards 11979-2[6] and 11979-9[7] for MTF measurements based on eye models. The device has a light source that emits at 546 nm. For different apertures it performs MTF measurements until the actual maximum frequency (from 0 to 370 c/degree, depending on aperture size). To measure the MTF of an IOL, the device uses a transilluminated pattern-edge, which is always located at an infinite distance. The instrument scans the image plane by moving the microscope at different focal points within the IOL's optical zone to collect best-focus planes. The scans give the MTFs at different positions and they actually form the axial MTF when they are joining together. Both MIOLs' optical quality was assessed at a well-centered position. The lenses were immersed in saline solution (refractive index: 1.335) and then were placed in a wet cell.

Results

Figure 2 shows the aMTF of the bifocal 2(a) and the trifocal lens 2(b) for a range of spatial frequencies up to 36 c/degree. The aMTF, as mentioned before, is the result of consecutive MTF measurements at different image planes across a range of spatial frequencies. In these graphs the optical behavior of the two different MIOLs designs can be observed at different focal planes and spatial frequencies. The color bar that accompanies the figure indicates the MTF values. Both lenses provide a focus for far (0 D) and near vision. As it can be observed from the graphs, the far focus of the bifocal IOL yields better optical quality than the far focus of the trifocal. In addition, the trifocal lens provides a distinct focus for the intermediate vision (around -2 D).

The behavior of the main foci of MIOLs under different defocus conditions and spatial frequencies is a very important factor to evaluate. For that reason, several defocus intervals (0.50 D, 0.75 D and 1 D) were set at the dioptric range of the lenses. These intervals defined the main foci of the MIOLs and allowed for quality evaluation in terms of defocus tolerance. Moreover, within the same defocus intervals we evaluated the optical quality that the foci yielded for different maximum spatial frequencies (7.5 c/degree, 15 c/degree, 30 c/degree).

Figures 3 and 4 show the variation in volume's values within different defocus intervals in a range of spatial frequencies until 36 c/degree, when VUaMTF was applied to evaluate the optical quality of the IOLs under study. The calculations were done for the different selected defocus intervals and maximum spatial frequency intervals. The values have been normalized by the values of a monofocal IOL in an interval of 1 D for a a maximum spatial frequency of 30 c/degree that corresponds to a 20/20 Snellen visual acuity. Figure 3 represents the VUaMTF values for the far 3(a) and the near focus of the bifocal IOL 3(b). Figure 4 shows the VUaMTF values for the far 4(a), the near 4(b) and the intermediate 4(c) focus of the trifocal IOL. Due to its design that allows a distribution of light in three foci, the trifocal IOL provides notable results in terms of optical quality for intermediate vergences.

In addition to Figures 3 and 4, Table 1 shows the numeric values of VUaMTF (normalized by the VUaMTF values of the monofocal IOL) for the different maximum spatial frequency and defocus intervals of the far and the near focus of the bifocal lens. Subsequently, Table 2 shows the VUaMTF values for the far and the near focus of the trifocal lens including also the intermediate focus.

Discussion

An ideal optical system exists only under ideal conditions that are not possible to reach in the real world. When the performance of an optical system is evaluated, a number of factors that influence its function must be taken into account (e.g. diffraction, relative illumination, etc.). The existence of metrics based on WFE, PSF and OTF[1-4] is essential to estimate an optical system's performance and to ensure that the system will be able to meet its objectives.

Metrics based on the MTF are commonly used for evaluating in vitro the optical quality of IOLs. In previous studies,[14,16-19] a metric widely used is the average MTF. The average MTF is the value of modulation averaged in the range of spatial frequencies from 0 c/mm to 100 c/mm. This metric has been proved[12,15] to be proportional to the area under the MTF, which has been used in other studies[20] for optical quality assessment. In some studies, the TF-MTF[13,19] has been used in order to assess the defocus tolerance of IOLs. In the aforementioned studies, the MTF and the TF-MTF of IOLs have been presented as separate entities to describe the optical quality of the lenses.

In this paper, a metric (VUaMTF) for assessing in vitro the optical quality of optical elements has been proposed. VUaMTF is based on volume calculation under the aMTF by setting different defocus and spatial frequency intervals. VUaMTF depends on three parameters (dimensions): the defocus interval, the range of spatial frequencies and the optical performance (MTF values).

A similar method, the Defocus Transfer Function (DTF) that is a 2 dimensional function whicht can be useful to characterize optical systems with circularly symmetric pupils, was previously proposed.[21]. The function analyzes the effect of defocus on the OTF taking advantage of the symmetry of the circularly symmetric pupil. DTF was proposed as a theoritical scheme for assesing the optical quality of intraocular lenses. Most comercially available devices for assesing the optical quality of intraocular lenses comply with the ISO standards (ISO 11979-2[6] and ISO 11979-9[7]) and calculate the MTF curves through an intensity profile that does not give information about the PSF or the OTF.

Calculations with VUaMTF can be performed at any desirable vergence. In the case of MIOLs, the key parts are their main foci that aim to provide optimum optical quality at different distances. In order to evaluate the optical quality of the MIOLs in this study, it was essential to set up intervals on their dioptric range to define the main foci. The number of intervals that were used for each lens relied on their design. For the bifocal IOL two intervals were used whereas for the trifocal were used three.

VUaMTF can be used as a tool to compare in vitro the optical quality of different IOLs revealing their optical performance and highlighting advantages and disadvantages between different lens types. For example, a comparison between two IOLs can be carried out keeping fixed the defocus interval and vary the spatial frequency interval or vice versa. Thus, the lens with the greatest VUaMTF value will be the lens with the best optical performance. In this study, the far focus of the bifocal yielded always higher values than the far focus of the trifocal. This difference is a result of the different lens design. As was previously described in the methodology, the optics of the bifocal lens allow for higher distribution of light in the far focus comparing to the trifocal.

The range of the intervals with VUaMTF is adjustable. This is an advantage that can be used to test the defocus tolerance of the lens (by increasing/ decreasing the defocus interval) and also to estimate the optical quality that it provides at different spatial frequencies. Figures 3 and 4 and Tables 1 and 2, demonstrate that VUaMTF gave the possibility of optical quality assessment of both MIOLs in several spatial frequencies and defocus intervals. This can be related to different visual tasks (depending on the spatial frequency) and to the defocus tolerance (different distances at which the tasks are performed).

A limitation of VUaMTF could be the fact that is summarizing the information of the three parameters to one numeric value. For example, an IOL with high MTF values but with a pronounced MTF decay can have the same VUaMTF value with an IOL that yields lower MTF value but shows a mild decay. This limitation comes from the volume calculation (i.e. the volume under both surfaces could be the same). Nevertheless, similar situations can be spotted in all the metrics that take into account areas or volumes calculations (for instance, the area under the MTF for a limited maximum frequency).

Another limitation of VUaMTF is that it can be applied only for rotationally symmetric lenses, tested in a well-centered position to avoid phenomena as decentration and tilt. It is known that the position of an IOL changes after is implanted. This is a result of contracting forces generated mainly by the capsular's bag shrink that leads to postoperative axial movement of the lens.[22] Therefore, phenomena such as decentration, tilt and rotation (rotation is the most important factor of optical quality degradation in cases of toric IOLs[23]) can occur. These phenomena can have an important impact on the visual outcome (e.g. decreased depth of focus or out of focus images) if the amounts are larger than the acceptable limits.[24] Under such conditions volume calculations under the aMTF will be inaccurate due to the fact that aMTF is the result of one-dimension averaged rMTF curves. For those cases, more complex schemes are needed to describe adequately the effects.

Clinicians should always treat the results of in vitro MTF evaluations of IOLs carefully. In a previous study[25], it was demonstrated that an increment of a certain amount in MTF does not correspond to an increment of the same amount in the contrast sensitivity function (CSF) of the human eye. By using an adaptive optic system, the authors corrected the higher order aberrations (HOAs) and the astigmatism of four subjects. Afterwards, then they compared the optical improvement by means of MTF with the visual improvement by means of CSF before and after correcting HOAs and astigmatism. Although the improved MTF was close to the diffraction limited MTF, the improvement in CSF was moderate. The authors justified this fact by the limitation that the neural CSF imposes.

In summary, VUaMTF is a metric that aims to compare objectively optical solutions in an easy and fast way by the use of a commercial bench and some basic calculations. In this paper we chose to focus on MIOLs due to the fact that nowadays they make a headway progress[26,27] in the field of refractive surgery. VUaMTF can provide valuable information about the optical tolerance to defocus and the optical quality of a MIOL allowing also for comparisons between different lenses. Nevertheless, VUaMTF is not restricted only to MIOLs: it can be applied to evaluate the optical quality of every IOL and furthermore, can be generalized to determine the optical quality of any rotationally symmetric optical system by means of aMTF.

What was known

- For assesing the in vitro optical quality of optical solutions such as IOLs, the MTF is the established scientific method widely used. Based on MTF several metrics have been developed to ensure the minimum standard of IOLs.

What this paper adds

- VUaMTF is a metric that is based on volume calculation under the surface defined by the aMTF. This metric offers an easy and objective way to evaluate the optical quality of rotationally symmetric optical elements by the use of a commercial bench and some basic calculations.

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Figures' Captions

Figure 1. Representation of the aMTF of the bifocal IOL in two dimensions as a function of defocus for a 3mm aperture size (1(a)). The color bar indicates the MTF values. Figures 1(b), 1 (c) **i**nterpretate Figure 1(a); A horizontal profile (line 1) shows the MTF of the far focus in the range of spatial frequencies (1(b)). A vertical profile (line 2) shows the MTF for a particular spatial frequency in the dioptric range of the lens (1(c)). The selected profile here corresponds to the TF MTF of the lens at the 15 c/degree. VUaMTF explanation. In Figure 1(a) a defocus interval (Dy) of 1 D range has been chosen in order to define the far focus of the bifocal lens in a range of spatial frequencies (Dx). Then, the VUaMTF metric applied to calculate the volume under the surface until the 15 c/degree spatial frequency.

Figure 2: aMTF representation of the bifocal 2(a) and the trifocal 2(b) lens up to 36 c/degree spatial frequency, for a 3mm aperture size. The color bar indicates the MTF values. In the graphs are clearly distinct the far and the near focus of the bifocal and the far, the near and the intermediate focus of the trifocal.

Figure 3. VUaMTF for different defocus intervals (0.5 D, 0.75 D, 1 D), for the far (a) and the near foci (b) of the bifocal lens at different spatial frequencies (up to 36 c/degree). The values are normalized by the values of a monofocal IOL in a 1 D defocus interval for 30 c/degree spatial frequency.

Figure 4. VUaMTF for different defocus intervals (0.5 D, 0.75 D, 1 D), for the far (a), the near (b) and the intermediate (c) foci of the trifocal lens at different frequencies (up to

30 c/degree). The values are normalized by the values of a monofocal IOL in a 1 D defocus interval for 36 c/degree spatial frequency.

Table 1. VUaMTF values for the far and the near focus of the bifocal lens, for different maximum spatial frequencies and defocus intervals. The values are normalized by the values of a monofocal IOL in a 1 D defocus interval for 30 c/degree spatial frequency.

Normalized VUaMTF values of the Bifocal IOL						
Freq (c/º)	**Far focus**			**Near focus**		
	Defocus Interval (D)			**Defocus Interval (D)**		
	0.5	**0.75**	**1**	**0.5**	**0.75**	**1**
7.5	0.16	0.23	0.31	0.11	0.17	0.22
15	0.27	0.40	0.51	0.18	0.27	0.34
30	0.45	0.62	0.77	0.29	0.40	0.49

Table 2. VUaMTF values for the far, the intermediate and the near focus of the trifocal lens, for different maximum spatial frequencies and defocus intervals. The values are normalized by the values of a monofocal IOL in a 1 D defocus interval for 30 c/degree spatial frequency.

Normalized VUaMTF values of the Trifocal IOL									
Freq (c/º)	**Far focus**			**Intermediate Focus**			**Near Focus**		
	Defocus Interval (D)			**Defocus Interval (D)**			**Defocus Interval (D)**		
	0.5	**0.75**	**1**	**0.5**	**0.75**	**1**	**0.5**	**0.75**	**1**
7.5	0.14	0.21	0.28	0.11	0.16	0.22	0.11	0.16	0.22
15	0.24	0.36	0.46	0.14	0.21	0.28	0.16	0.23	0.30
30	0.39	0.54	0.66	0.18	0.27	0.35	0.24	0.34	0.42